SENSITIVITY OF THE SPACE DEBRIS ENVIRONMENT TO LARGE CONSTELLATIONS AND SMALL SATELLITES

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ABSTRACT

Opportunities provided by small satellites in low Earth orbit (LEO) are anticipated to make a significant impact on the space economy through the delivery of important and innovative services. However, with plans by some companies to operate large constellations of small satellites in LEO, and with many small satellite launches forecast in coming decades, there is concern that existing debris mitigation measures will not be sufficient to counteract the impacts of this increased space activity on the LEO environment. Within this context, a team comprising engineers from industry, academia and the European Space Agency have performed an assessment of the potential impact of small satellites and large constellations on the space debris environment. This paper provides an overview of the work undertaken and the results that emerged.

1 INTRODUCTION

Low Earth orbit (LEO) is experiencing a renaissance thanks to increasing commercialisation of space. Small satellites have played a vital role in this revolution and they have a unique ability to bring new products and services to market at short timescales and for relatively low-cost. This has caused a dramatic increase in both the number of commercial actors within the space industry and the number of small spacecraft launched. With the expectation that this change will continue into the future, especially given plans to operate large constellations of communication satellites in LEO, there is some concern about the effectiveness and relevance of the existing space debris mitigation guidelines.

Whilst the long-term effects arising from the introduction of constellations and small satellites to LEO have been investigated in the past (e.g. [1-6]) few studies have been able to examine the sensitivity of the space debris environment to more than a limited set of parameters. As such, only a relatively incomplete understanding of the possible impacts of large constellations and small satellites on the environment has emerged. In fact, little is known about the measures that might be taken by large constellation or small satellite operators to enable to mitigate the effects of their activities on the space environment.

A recent initiative focused on large constellations, involving a number of European space agencies, was reported in [1] and highlighted the importance of post-mission disposal (PMD) measures on the mitigation of debris resulting from a 1080-satellite constellation. Separately, [2] computed collision probabilities and the number of collision avoidance manoeuvres for the proposed OneWeb constellation, with different assumptions for the success of the PMD, mission altitude and lifetime. The results underlined the sensitivity to the mission altitude and the PMD success, with the need for very high PMD success rates for mission altitudes that experience little atmospheric drag. Further, [3] found that some of the proposed large constellations can be expected to generate approximately one collision per year in total for the operational satellites and another two collisions per year for the disposed satellites.

In 2016 and 2017, a team comprising engineers from industry, academia and the European Space Agency performed a comprehensive assessment of the potential impact of small satellites and large constellations on the space debris environment. This assessment included: (1) a review of historical and proposed future small satellite activities and associated technologies; (2) a large number of long-term projections using three evolutionary codes; and (3) detailed analysis of the results of the first two activities, to understand the sensitivity of the debris environment to key satellite and constellation parameters. Initial results from the projections were presented in [6] and more detailed analyses of particular results are presented in [7-9]. This paper provides an overview of the simulation studies performed during the study and presents the key results and lessons learned.

2 METHODOLOGY

Three evolutionary debris models were used to perform long-term environment projections: the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) developed at the University of Southampton, the Long-Term Utility for Collision Analysis (LUCA) developed at Technische Universität Braunschweig, and the Space Debris Mitigation long-term analysis program (SDM) developed at IFAC-CNR.

The analysis was based on comparisons of long-term projections of the orbital object population ≥ 10 cm, under a variety of small satellite and mega-constellation scenarios, with a reference scenario comprising:

- Initial population: all objects ≥ 10 cm with perigee < 2000 km in orbit on 1 Jan 2013
- Future launch traffic: repeat 2005-2012 cycle
- Projection period: 1 Jan 2013 to 1 Jan 2213
- Post-mission disposal (PMD) of 90% of spacecraft and rocket bodies to a 25-year orbit
- No explosions
- No collision avoidance

The baseline constellation case, which was the same as reported in [1] and [6], then included the following in addition to the reference:

- Walker-delta constellation comprising 1080 satellites in 20 orbital planes at 1100 km altitude and inclined at 85°
- Constellation satellite design lifetime of 5 years, 200 kg and 1 sq. metre
- Constellation build-up phase from 1 Jan 2018 to 1 Jan 2021 with 20 launches per year and 18 satellites per launch
- Constellation replenishment phase from 1 Jan 2021 to 1 Jan 2070 (50 years) with 12 launches per year and 18 satellites per launch. Note that the first replenishment launches commenced on 1 January 2023
- PMD of 90% of constellation spacecraft to a 400 × 1100 km or "25-year" disposal orbit
- Immediate de-orbit of rocket bodies

The baseline small satellite case incorporated the medium launch rate scenario, based on models by [4] and superimposed on the reference case (Figure 1). A description of the small satellite launch traffic model as implemented in this study is provided in [8].

Variations of the constellation and small satellite parameters with respect to the baseline cases provided the set of simulation cases that were investigated. The variations considered for the constellation cases included mission lifetime, constellation altitude, number of satellites and spares, satellite characteristics and lifetime, and launcher behaviour, amongst others. The variations in the small satellite baseline case included the launch rate, the satellite size/form factor, the launch altitude, and post-mission disposal, amongst others.

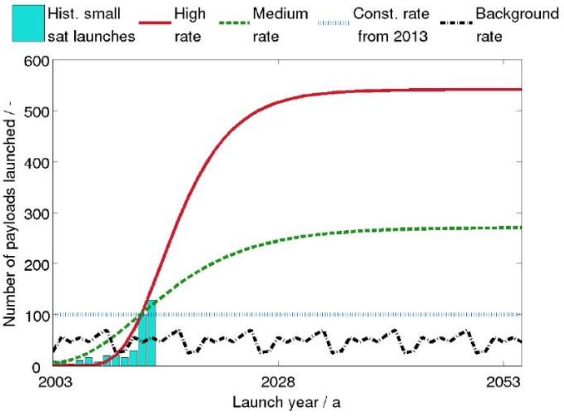


Figure 1. Launch rate of small satellites used for simulation studies. The medium rate was adopted for the small satellite baseline case.

For all of these cases 50 Monte Carlo (MC) runs were performed. Investigations by [10] and [11] have shown that sample sizes of 40-60 MC runs are needed for reliable estimates (within 10%) of the mean to be made.

For this study, three categories of evaluation metrics were used: (1) metrics based on averages (e.g of the number of objects or collisions) computed over all MC runs, (2) metrics based on the statistical variability in MC runs (so-called "criticality norms") and (3) metrics based on probabilistic assessments of the MC runs.

The sum of the differences between the averages (of the number of objects or the number of collisions) from a test case and the reference case, normalised by the standard deviation and weighted by the time interval, N, gives an indication of the criticality [12]:

$$C^* = \frac{1}{N}\sum_{i=1}^{N} C_i = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\bar{n}_{TEST}(i) - \bar{n}_{REF}(i)}{\sigma_{REF}(i)}\right) \qquad (1)$$

where $\bar{n}_{TEST}(i)$ is the number of objects or number of collisions in the small satellite/constellation test case at an epoch (year) given by i, $\bar{n}_{REF}(i)$ is the number of objects (or collisions) in the reference case and $\sigma_{REF}(i)$ is the standard deviation of the reference MC runs at the same epoch. Values of C_i and C^* (or "Cnorm" as they are referred to elsewhere in this paper) were evaluated over the number of years in the simulation, or at the end of the projection period.

The probability based metrics quantify the likelihood of there being a difference between the test case (i.e. with a constellation or small satellites) and a reference case, or the likelihood that the two cases are similar. The aim is to estimate the probability that the number of objects or collisions at any epoch and in a MC run drawn at random from the results of the test case is less than (or equal to) the number of objects or collisions at the same epoch in a MC run drawn at random from the results of the reference case:

$$P^* = \frac{1}{N}\sum_{i=1}^{N} P_i = \frac{1}{N}\sum_{i=1}^{N} P[n_{TEST}(i) < n_{REF}(i)] \qquad (2)$$

Values of P_i and P^* (or “P(T<R)” as they are referred to elsewhere in this paper) were evaluated over the number of years in the simulation, or at the end of the projection period. If the test case and the reference case are identical then P_i will be 0.5.

3 RESULTS

3.1 Reference case

The reference case provided an opportunity to compare the results of all three evolutionary models. Figure 2 shows the predictions of the number of objects made by DAMAGE, LUCA and SDM. For this case, SDM predicted the highest average number of objects throughout the projection period, followed (relatively closely) by DAMAGE and then LUCA. The latter model predicts a net decrease, on average, in the number of objects by the end of the projection period, compared with the number at the beginning. Whilst Figure 2 appears to show that the distribution of the final populations predicted by LUCA are significantly lower than the equivalent distribution predicted by either DAMAGE or SDM, the reality is that there is some overlap due to a number of outliers.

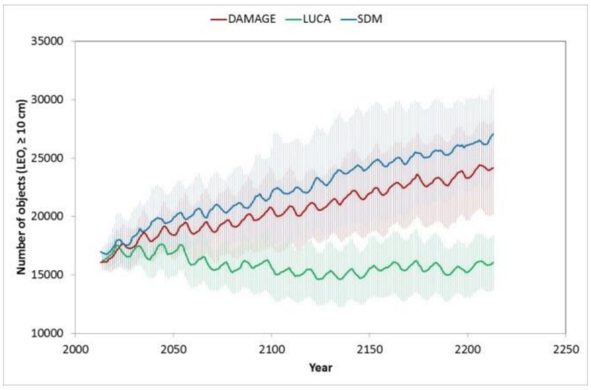


Figure 2. Effective number of objects over the projection period for the reference case.

The number of catastrophic collisions predicted by each model is shown in Figure 3. The SDM model predicts a catastrophic collision rate of 0.2/year (R^2 = 0.999), on average, whereas LUCA predicts a corresponding rate of 0.14/year (R^2 = 0.994). For the first 50 years of the projection, all three models predict catastrophic collisions at a rate of 0.2/year, on average.

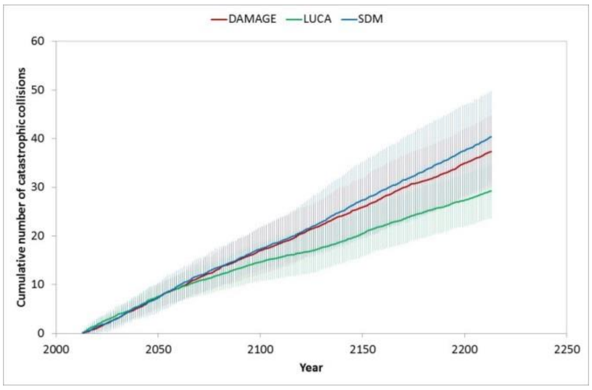


Figure 3. Evolution of the cumulative number of catastrophic collisions for the reference case.

3.2 Large constellations

As for the reference case above, the baseline constellation case was simulated using all three evolutionary models and the results below provide a comparison (Figure 4 and Figure 5).

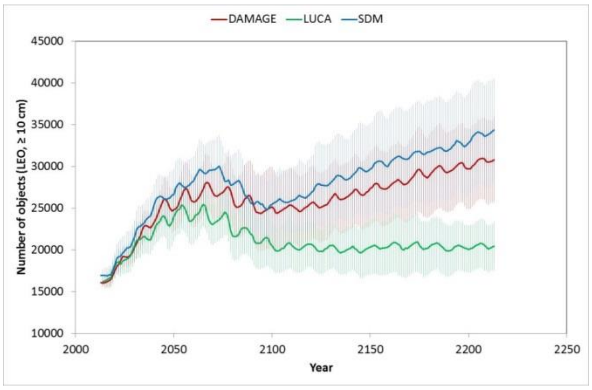


Figure 4. Effective number of objects over the projection period for the constellation baseline case.

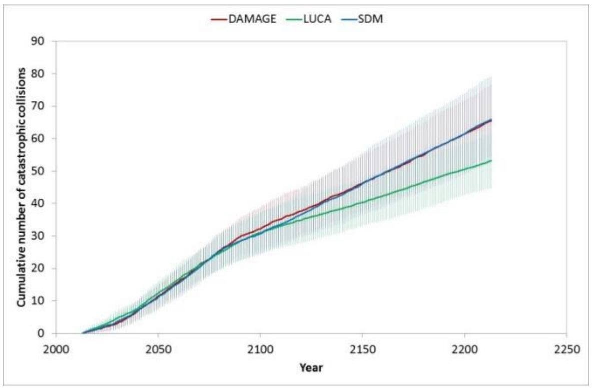


Figure 5. Evolution of the cumulative number of catastrophic collisions for the constellation baseline case.

These results are consistent with those presented in [1]. They show that the impact of the constellation on the orbital object population can be separated into three components: a quick population rise during the constellation build-up and replenishment; a period of population decay as PMD measures reduce the number of constellation satellites; and a long-term, gradual increase in the population due to collisions involving long-lived, failed constellation satellites.

The sections below describe the results obtained through the variation of the constellation parameters. They are presented in order of their impact on the space debris environment, as determined using the evaluation metrics outlined above.

3.2.1 Post-mission disposal (PMD)

Constellation PMD was investigated in several cases. In many of the simulations performed, at least one other parameter was also varied.

Initially, the PMD success rate was selected from the set {60%, 80%, 90%, 95%, 100%} and two different types of disposal orbit were investigated: (1) a disposal orbit with a fixed perigee (400 km) and apogee (1100 km), with a nominal lifetime of approximately 20-25 years (results shown in Figure 6), and (2) a disposal orbit with a nominal residual lifetime of 25 years. The two approaches yielded consistent results, with very high numbers of objects and catastrophic collisions generated for a PMD success rate of 60%. The number of objects and collisions decreased (following a quadratic fit, R^2 = 1.0 for both number of objects and collisions) as the PMD success rate increased.

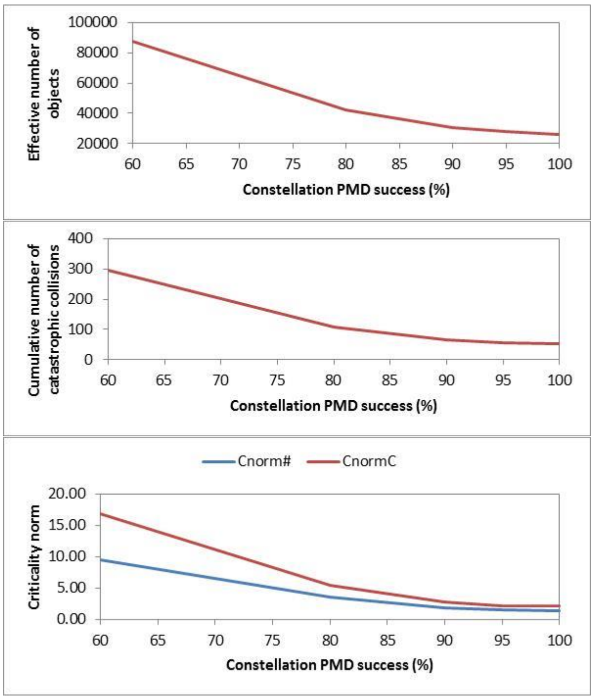
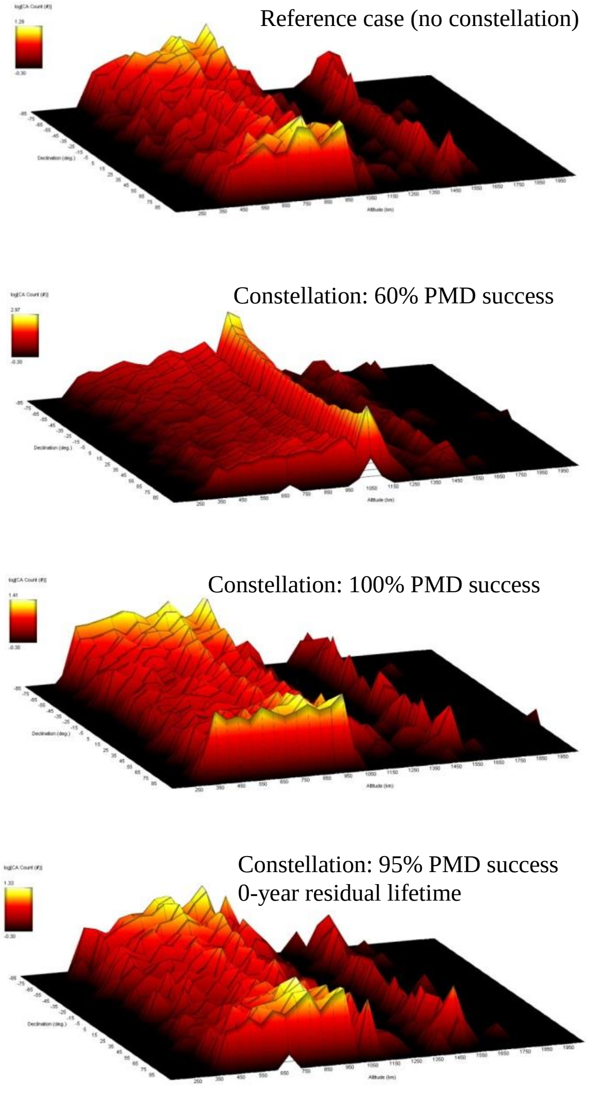


Figure 6.Effect of constellation post-mission disposal success rate on key summary metrics computed by DAMAGE for a 400 × 1100 km disposal orbit.

Whilst high PMD success rates resulted in fewer failed satellites at the constellation altitude, they also led to higher numbers of satellites traversing large parts of the LEO region in disposal orbits and, consequently, a higher proportion of collisions involving constellation and background objects. Indeed, the flux on the International Space Station (ISS) increased five- to ten-fold, compared with the reference case, during the operational lifetime of the constellation. Similar results were reported by [3]. So, it is not correct to assume that even perfect adherence to PMD guidelines will result in no impact on the environment.


Reference case (no constellation)

Constellation: 60% PMD success

Constellation: 100% PMD success

Constellation: 95% PMD success
0-year residual lifetime

Figure 7. Comparison of the spatial distribution of collisions computed by DAMAGE, for PMD corresponding to disposal orbits with 25 years residual lifetime. Note the change in scale of the z (depth) axis between the plots.

In spite of the seemingly less-than-optimal outcome for high PMD success rates, it is important to recognise that the discussion here relates to *relative* differences; in *absolute* terms there were approximately five times fewer constellation-versus-background catastrophic collisions for a 100% PMD success rate, compared with a 60% PMD success rate. Nevertheless, if the aim is to remove *any* impact of a constellation on the background population, measures that address the constellation-versus-background collisions below the constellation altitude will be required. High PMD success rates consistently reduce the number of objects and the number of catastrophic collisions, in absolute terms, while shorter residual lifetimes limit the impact of the constellation on the background population (Figure 7).

The results can also be used to find different combinations of the two PMD measures (success rate and residual lifetime) that tend to produce the same outcome, in terms of the number of objects and catastrophic collisions (Figure 8). For example, a 90% PMD success rate with a 25-year residual lifetime resulted in the same cumulative number of catastrophic collisions (75) as an 85% PMD success rate with a 5-year residual lifetime, although there were more objects in LEO at the end of the projection period. Whilst the trade-off is biased in favour of the PMD success rate, the results do suggest that mission designers may have some flexibility in their approach to PMD, especially if high PMD reliability is a challenge.

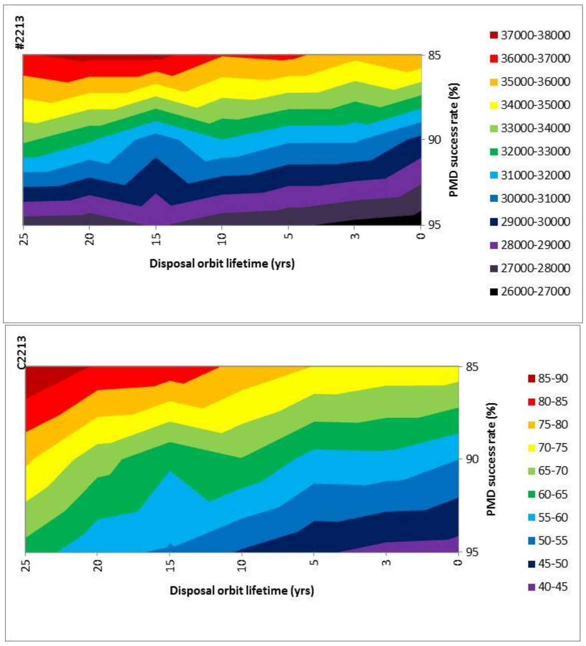


Figure 8.Effect of constellation PMD success rate and residual lifetime of disposal orbit on the number of objects (top) and the cumulative number of catastrophic collisions (bottom) in 2213.

Reference [1] investigated different disposal orbit options and found, in general, that elliptical orbits with short residual lifetimes were desirable. Here, a greater variety of disposal orbit options was investigated using DAMAGE and LUCA. These models predicted a comparable average number of catastrophic collisions for each of the disposal orbits investigated ($R^2 = 0.866$) and the subsequent criticality norm values for the catastrophic collisions were similarly close ($R^2 = 0.867$).

The surface charts in Figure 9 show that the impact of the constellation disposal orbit on the LEO environment is not simply a matter of whether the orbit is elliptical or whether the residual lifetime is short. Indeed, both DAMAGE and LUCA predicted relatively high number of objects and catastrophic collisions for the 300 × 300 km disposal orbits, which had the shortest residual lifetime. It is likely that the volume of space at this altitude is insufficient to support the number of satellites using it for disposal. In addition, simply lowering the perigee of the disposal orbit to 300 km or 400 km altitude without also adjusting the altitude of the apogee (with respect to the constellation altitude) did not lead to a reduced impact on the environment, even though the residual lifetimes were relatively short and the satellites could be distributed through a large volume of space because of the elliptical orbits. It is recommended that constellation operators perform a trade-off with respect to the environmental impact and delta-V, on a case-by-case basis, with the aim of finding achievable disposal orbits that limit impacts on the environment.

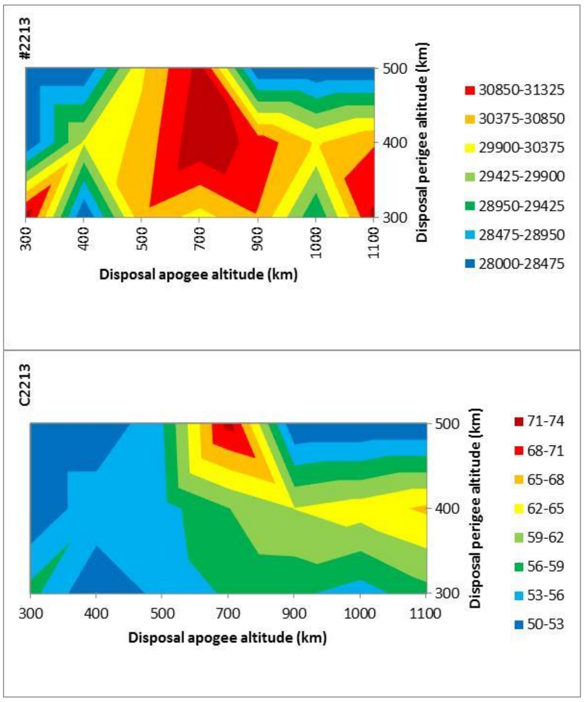


Figure 9.Effect of constellation disposal orbit apogee and perigee altitudes on the number of objects in orbit at the end of the projection period (top), and on the number of catastrophic collisions (bottom).

Given the potential for the disposal orbits of constellation satellites to intersect the orbits of objects in the background population, it was necessary to consider the effects of different PMD behaviour and launch activity in the background population too. The results from DAMAGE and LUCA simulations for a range of background behaviours showed very good agreement with respect to the trends ($R^2 > 0.9$). As expected, when the PMD success rate for the background population changed from 90% to 60% the number of objects in LEO at the end of the projection period increased by approximately 10,000 in the DAMAGE results with an additional seven catastrophic collisions, on average. There was a corresponding decrease in the proportion of catastrophic collisions involving constellation objects (from 47% to 38%) but no change in the proportion of those collisions that were self-induced or involved a background object. In contrast, doubling the launch traffic resulted in a greater proportion of constellation-versus-background catastrophic collisions.

In the case where the constellation and the background PMD success rates were sub-optimal, a large fraction (88%) of the resulting > 300 catastrophic collisions in the environment involved an object from the constellation and 69% of those collisions (about 180) were self-induced, on average. This does suggest that the constellation "comes off worse" in this type of situation and this may be an incentive for constellation operators to aim for high reliability.

Overall, the results from LUCA and DAMAGE for the PMD cases demonstrate the importance of compliance with this debris mitigation guideline by all space users sharing the LEO region. The results also highlight the need for constellation operators to build-in a resilient approach to their mission operations and debris mitigation measures, should the background launch activity change in a manner that leads to an increased potential for conjunctions with constellation satellites.

3.2.2 Constellation launch vehicle behaviour

The behaviour of the launch vehicles used to orbit the constellation satellites represents an important parameter with respect to the LEO environment. In [4], the role of the launch vehicle upper stages was neglected. Here, we have investigated a range of possible behaviours for these objects – primarily relating to PMD success rate and the residual lifetime of the disposal orbits the stages are transferred into, but also considering the payload release altitude and the impact of increased background launch activity.

There was significant, detrimental effect on the LEO environment when the launch vehicles deployed their payloads at the constellation altitude and then did not perform any post-mission disposal. In addition to the baseline case, the number of objects in LEO at the end of the projection period was > 200,000 and > 500 catastrophic collisions had taken place. Nearly 100% of all catastrophic collisions and nearly 100% of all fragments generated over the projection period were the result of a constellation object. In addition, one-third of the catastrophic collisions involved an object from the background population. As with the constellation satellites, implementing and increasing the PMD success rates for upper stages in this case resulted in substantial benefits to the environment. Limiting the time spent by these objects in the LEO region to 10 years also provided some benefit.

The effect of non-compliant launch vehicles can be mitigated if the satellite release occurs at relatively low altitude because the upper stages can be removed by atmospheric drag. In fact, when satellites were deployed from the launch vehicle at an altitude of 400 km the impact on the LEO environment was no different to that of the baseline case, in which the launch vehicle upper stages were assumed to de-orbit immediately (see Figure 10). Payload releases at altitudes up to approximately 600 km were seen to have no significant impact on the LEO population or cumulative number of catastrophic collisions. So, a prudent approach to the deployment of constellation satellites would be to release them at low altitudes from where they can perform an orbital transfer (either impulsive or low-thrust) to the mission altitude; any upper stage that subsequently fails to comply with post-mission disposal guidelines will decay relatively quickly and have minimal impact on the LEO environment.

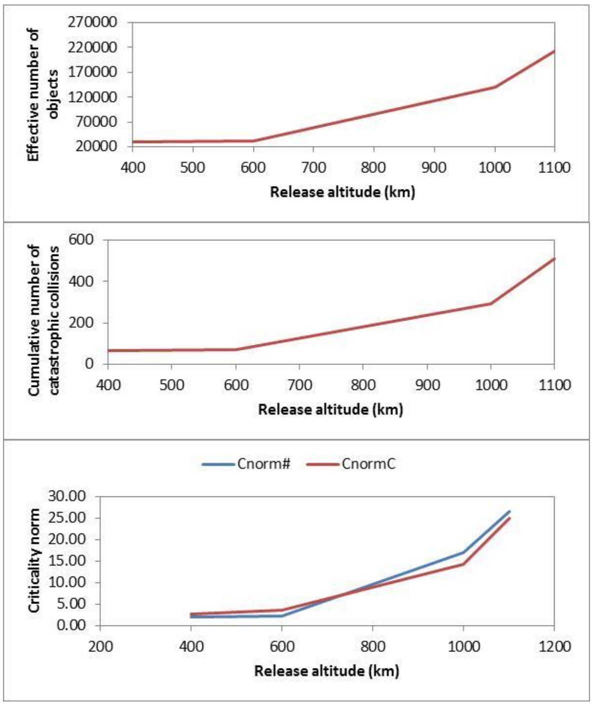


Figure 10. Effect of payload release altitude on key evaluation metrics when upper stages are included without PMD.

3.2.3 Background explosions

Another aspect of the background behaviour that was investigated in this study was the explosion rate. Again, DAMAGE and LUCA were used to evaluate the impact of two explosion rates, in addition to the no-explosion, baseline case: two explosions per year and five explosions per year. Perhaps unsurprisingly, the results indicate that the number of objects and the cumulative number of catastrophic collisions in LEO by the end of the projection period was proportional to the background explosion rate. The effect, however, appeared to be limited to a relatively small increase in the average object population, when the explosion rate increased from two to five per year, with no significant change in the average number of catastrophic collisions. The relatively constant values for the criticality norms calculated from the DAMAGE results also suggest little impact on the distribution of outputs from the MC runs.

The DAMAGE results also show a direct impact of the background explosions on the constellation traffic: as the background explosion rate increased, so too did the fraction of catastrophic collisions involving a background object and a constellation object. Whilst the effect was small, nevertheless it demonstrated the interdependence of the two populations.

3.2.4 Constellation size

In general, the number of objects and the number of catastrophic collisions in LEO at the end of the projection period were proportional to the size of the constellation – i.e. the number of satellite members (Figure 11). For relatively small constellations (e.g. a few hundred satellites) the impact on the LEO environment was indistinguishable from the reference case ($p >> 0.05$ in a Wilcoxon test). In fact, there was a probability of more than 25% that the number of objects predicted to be on-orbit at any point in the projection period was less than the number of objects predicted for the reference case (and also for the cumulative number of catastrophic collisions). Increasing the size of the constellation beyond approximately 600 satellites resulted in the emergence of a significant difference in the $P(T<R)$ metric, with respect to the reference case.

Increasing the constellation size resulted in a non-linear (quadratic; $R^2 = 1.0$) increase in the number of self-induced catastrophic collisions but a linear increase ($R^2 = 0.993$) in the number of constellation-versus-background catastrophic collisions. For the largest constellation studied, the average catastrophic collision rate in the LEO environment was higher than one per year, with 90% of those collisions involving at least one constellation object and generating 70% of all fragments.

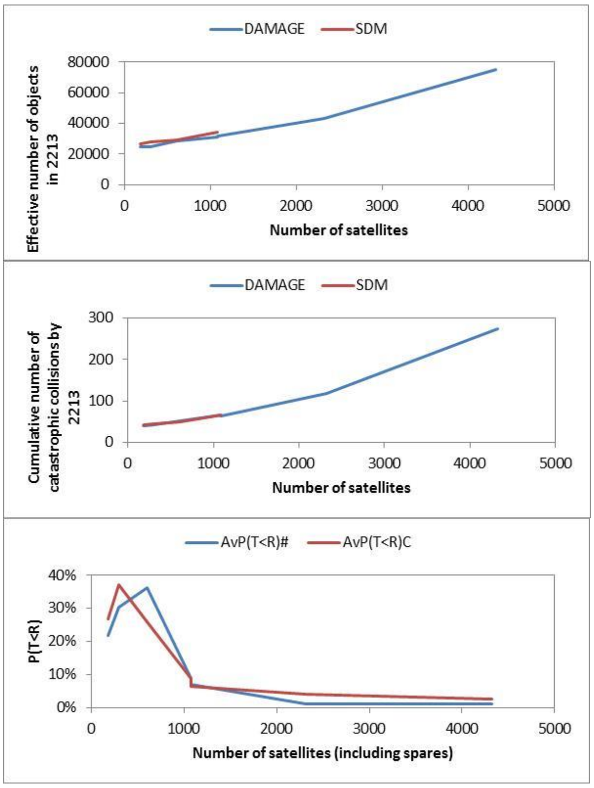


Figure 11.Effect of constellation size on key summary metrics computed by DAMAGE and SDM.

In general, the use of spare satellites reduced the impact of the constellations on the LEO environment. In addition, the benefits were proportional to the fraction of the constellation satellites that were spares, such that the largest constellation (3000 satellites with 18 spares per plane) saw decreases of 24.2% in the number of objects in the year 2213, and of 33.74% in the number of catastrophic collisions by 2213. Further work is required to evaluate the sensitivity of these benefits to the number/proportion of spare satellites and also to determine the impact of the use of storage orbits above or below the constellation. However, the first pass through this case provided some evidence that the use of spare satellites can be encouraged.

3.2.5 Constellation satellite characteristics

All three evolutionary models were used to investigate the influence of the mass and area of the constellation satellites on the LEO environment. The DAMAGE simulations covered 14 cases, whilst LUCA and SDM evaluated five and three cases, respectively. In general, DAMAGE predicted fewer objects but more catastrophic collisions by the year 2213 for all three cases, compared with SDM, but the overall trends, with respect to satellite mass and area, were the same for both models ($R^2 > 0.8$). In contrast, the correlation between the results from DAMAGE and LUCA for their five common cases was poorer. For LUCA, the effect of satellite mass and area on the number of objects and the cumulative number of catastrophic collisions in 2213 was not as pronounced as it was for DAMAGE, a result that was likely due to different implementations of the breakup model and orbital propagator.

The DAMAGE results indicate that the constellation satellite mass and area played two distinct roles in the evolution of the LEO environment (Figure 12). Firstly, increasing the cross-sectional area of the satellites from 1 sq. m to 6 sq. m resulted in a significantly higher collision rate, because the collision probability is proportional to the cross-sectional area. Due to the high altitude of the constellation, away from all but the slightest effects of atmospheric drag, the increase in area did not translate into faster decay rates, which meant that the larger, failed satellites were exposed to higher debris fluxes for long periods. In turn, the high collision rates generated a higher number of fragments that, again, were slow to decay from the constellation altitude and ultimately enhanced the population. Secondly, increasing the mass of the satellites from 100 kg to 400 kg resulted in a higher number of fragments being generated per collision, because the number of fragments is proportional to the mass according to the NASA standard breakup model [13]. However, these fragments did not add significantly to the collision rates that were observed (bottom panel of Figure 12).

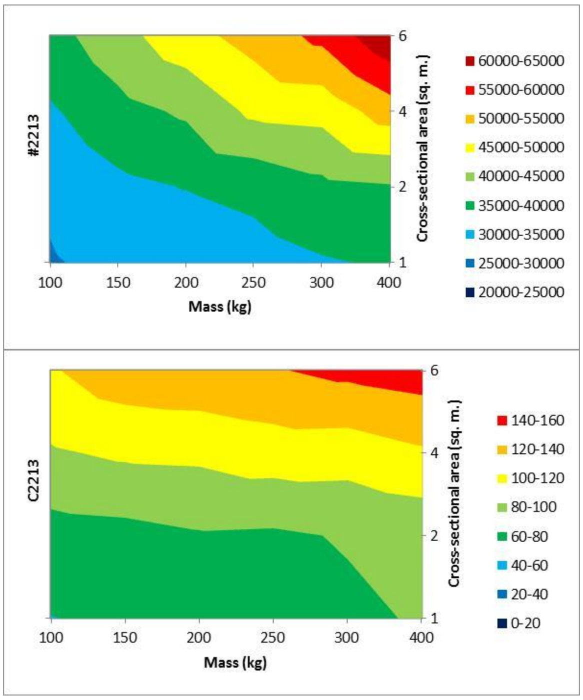


Figure 12.Effect of constellation satellite mass and area on the number of objects (top) and cumulative number of catastrophic collisions (bottom) in the year 2213, computed by DAMAGE.

For constellation satellites of 400 kg and 1 sq. m, approximately half of all the catastrophic collisions in LEO involved a constellation object, the same outcome for satellites of 200 kg and 1 sq. m. In contrast, changing the area from 1 sq. m to 6 sq. m. led to the involvement of a constellation object in approximately 80% of all catastrophic collisions, regardless of the satellite mass.

Another constellation satellite characteristic investigated was the lifetime. In the baseline case, the lifetime of the satellites was fixed at five years. Longer satellite lifetimes led consistently to fewer objects in the LEO environment and fewer catastrophic collisions. In addition, the ability to extend satellite lifetimes beyond the design life also led consistently to the same benefits. The change from a 3 year lifetime to a 7 + 3 year lifetime (where satellites can continue to operate for up to three years beyond their nominal design life) led to a reduction in the mean number of objects from 40,720 to 28,921; a change of 29%. A change of 48% was observed for the mean number of catastrophic collisions between these two cases.

3.2.6 Constellation mission lifetime

DAMAGE and LUCA were consistent in predicting a greater impact on the LEO environment from constellations with longer mission lifetimes, compared with constellations with shorter mission lifetimes, both in terms of the number of objects in the environment at the end of the projection period and the number of catastrophic collisions. Indeed the number of catastrophic collisions and the number of objects at the end of the projection period were directly proportional to the mission lifetime.

For relatively short mission lifetimes (e.g. < 30 years) there was a relatively high probability (> 30%) that a DAMAGE MC run from the constellation case would predict a lower number of objects and catastrophic collisions than a MC run from the reference case. For long mission lifetimes (e.g. > 80 years) DAMAGE predicted that constellation objects were involved in more than 50% of all catastrophic collisions in LEO, which generated more than 40% of all fragments. Consequently, there are clear benefits that arise from limiting the duration of constellation activities (or from monitoring and re-evaluating constellation activities at regular intervals throughout the mission).

3.2.7 Constellation satellite explosions

The impact of explosions within the constellation was examined by DAMAGE and LUCA. At the highest explosion rate considered (4% of failed constellation satellites) there were approximately 45 to 55 explosions within the constellation mission lifetime with each explosion generating 238 fragments according to the NASA standard breakup model.

The size of the 2213 population increased by 35% from 30,816 objects (for no explosions) to 41,503 objects (for the highest explosion rate), on average. The effect of the explosions on the number of catastrophic collisions was approximately half that observed for the number of objects, with only an 18% increase in the number of catastrophic collisions for the worst explosion case, compared with the baseline. In contrast, the LUCA results suggest very little impact was made by the constellation satellite explosions on the average number of objects or on the average number of catastrophic collisions, even for the worst-case explosion rate investigated. For the 4% explosion rate case, the LUCA results show an increase of 10% in the 2213 population and an increase of less than 0.05% for in the number of catastrophic collisions.

3.2.8 Constellation altitude

It was apparent that for either disposal scheme (400×1100 km disposal orbit, or "25-year" disposal orbit), constellations located at relatively low altitudes tended to result in fewer objects on-orbit by the end of the projection period, almost certainly due to the greater atmospheric drag acting on any satellites failing before the start of the post-mission disposal phase. However, the catastrophic collisions involving a constellation object were more likely to involve an object from the background population when the constellation was at lower altitudes (e.g. on average, 60% of catastrophic collisions involving a constellation object also involved an object from the background population when the constellation was located at 700 km, whereas only 20% involved two objects from the constellation). In general, more self-induced collisions in the constellation take place when the constellation is at a higher altitude than when it is located at a lower altitude.

At a simplistic level, the selection of constellation altitude will be a trade-off between the relative benefits to the environment overall (i.e. aim for a constellation at low altitude) and the relative impacts on other space users (i.e. aim for a constellation at high altitude to avoid these). This trade-off is affected by other factors such as the constellation satellite mass and area characteristics, which affect the rate of decay and collision probability, and the number of satellites needed to achieve the required coverage.

3.2.9 Multiple constellations

The SDM model was used to investigate the impact of multiple constellations on the LEO environment. For these simulation cases the following parameters were adopted (1) two identical 1080-satellite constellations, both based on the baseline case, with one constellation at 1100 km and the other at 1300 km altitude; or (2) three constellations, including the baseline constellation at 1100 km, a 1400-satellite constellation with 35 planes at 1200 km and inclined at 45°, and a 120-satellite constellation with 12 planes at 1200 km and inclined at 85°. All of the satellites were assumed to be 200 kg in mass and 1 sq. metre in area, and the constellation mission lifetimes were assumed to be 50 years.

As each constellation adhered to the same post-mission disposal practice and success rate (90%), the number of failed satellites left on-orbit after the constellation mission was directly proportional to the number of satellites launched to maintain the constellation. As such, the number of objects in the LEO environment for the multiple constellation cases was always higher than it was for the baseline case. In addition, the growth in the object population that occurred after the end of the constellation missions was at a higher rate for the multiple constellation cases than for the baseline case; again, due to the larger population of failed constellation satellites. It is straightforward to conclude, therefore, that increasing the number of constellations operating in the LEO region will lead to proportionally greater impacts on the environment unless measures are taken to address the additional traffic.

3.2.10 Constellation satellite failures

The satellite failure model in DAMAGE, which is based on a two-Weibull mixture model, was modified to account for enhanced failure probabilities at different phases of the satellite life (early/infant, midlife and end of life). In all cases the overall probability of failure was still set by the post-mission disposal success rate (= 1 – PMD success rate) and the failure model was used to determine at what stage of the satellite's lifetime that the failure occurred (Figure 13).

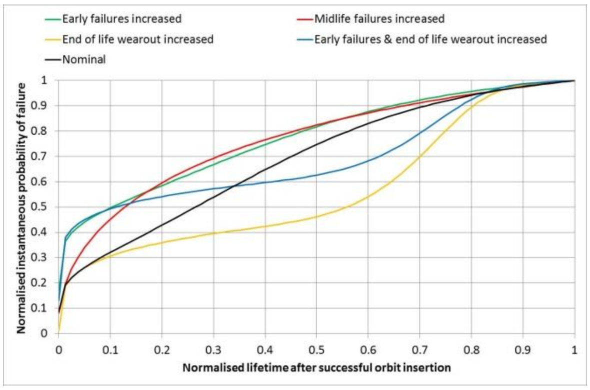


Figure 13.Satellite failure probabilities for five failure model versions in DAMAGE.

The impact of the failure model depended on the constellation "concept of operations". For satellites using chemical propulsion the failure always occurred during the constellation operations, regardless of the failure model, because all orbit transfers were assumed to be instantaneous. This meant that failed satellites were consistently at the constellation altitude. In contrast, satellites that used electric propulsion failed at one of three points: during the ascent (i.e. on near-circular orbits below the constellation altitude), during the constellation operations (i.e. on circular orbits at the constellation altitude), or during the initial descent towards the final disposal orbit (i.e. on elliptical orbits below the constellation altitude). The likelihood of failure at any of these points was determined by the failure model used.

In general, the electric propulsion option resulted in fewer catastrophic collisions at all release altitudes, compared with the chemical propulsion option, regardless of the failure model. The benefits gained from the use of electric propulsion almost certainly come from the changed concept of operations, which permitted satellites failing during the ascent phase from low altitude to be removed from the environment through atmospheric drag or, even in a worst case scenario, to be away from the constellation.

The results indicated that if failures were more likely to occur near to the beginning or end of life of the constellation satellites then the number of objects and the number of catastrophic collisions was reduced overall, compared with the baseline case (which utilised the nominal failure model shown in Figure 13). Further, the probability-based metrics indicate that early failures led to MC run outputs that were close to those produced for the reference case (P(T<R) for the number of objects at 2213 = 44.25%, P(T<R) for the cumulative number of collisions by 2213 = 43.56% and Similarity = 88.5%). Early failures not only reduced the number of catastrophic collisions in an absolute sense (and in spite of the replacement of failed satellites), this type of failure also reduced the proportion of catastrophic collisions that involved a constellation object by half, from 43.2% for the baseline case to 19.6%.

Clearly a failure model is not something that can be selected by the satellite designer/operator; they cannot choose for a satellite to fail early in its lifetime rather than late. However, the operator can choose to release their satellites from the launch vehicle at a low altitude such that any satellites that do fail early will be removed by the natural effects of atmospheric drag in a relatively short period of time and without impacting the constellation or the background population in any significant way. The benefits arising from such an approach may be extended if the operator employs a "checkout" period at the beginning of life, whereby the critical systems of the satellites are tested to ensure nominal performance, and satellites proceeding to the constellation altitude are the most reliable.

3.2.11 Other constellation parameters

Two constellation geometries were studied using DAMAGE: Walker-star and Walker-delta. For a constellation with orbital planes inclined at 85°, the choice of the constellation geometry made no significant difference to the number of objects or the number of catastrophic collisions. In addition, the inclination of the orbital planes was also considered: higher inclinations (up to 85°) led to an increased number of catastrophic collisions at the constellation altitude (1100 km) and between 400 km and 700 km, and a higher proportion involving constellation objects.

An option that can be considered by constellation operators is to introduce a separation in altitude between the orbital planes. In the simulations investigated here, each successive plane was simply placed at a higher altitude than the preceding one, without considering the consequences for the coverage. The DAMAGE model was used to simulate three constellations, each with a different separation between the planes (2 km, 5 km and 8 km) as well as the baseline case.

The results show that separating the planes in the constellation led to fewer objects remaining in the LEO environment at the end of the projection period, and fewer catastrophic collisions. However, the benefits diminished as the separation increased. In the best case (8 km separation) there were 25% fewer catastrophic collisions and 11% fewer objects by 2213, compared with the baseline case. Further work is needed to understand the scope of possible benefits that could be achieved by separating the orbital planes, with simulations needing to incorporate plausible scenarios for achieving such separations that also account for the changing coverage patterns.

In the previously reported simulation cases, it was assumed that the constellation satellites were able to perform collision avoidance manoeuvres with 100% success. This assumption was varied here in order to evaluate the criticality of the collision avoidance capabilities for the constellation. The collision avoidance success rate was set to one of the following values: 50%, 70%, 90% or 100%. The results indicate that the number of objects in the LEO environment and the number of catastrophic collisions was inversely proportional to the collision avoidance success rate, but the difference between the best case collision avoidance rate (100%) and worst case (50%) was relatively small (7% change in the number of objects and 11% change in the number of catastrophic collisions). Nevertheless, the results provide evidence for good surveillance and tracking of constellation satellites in support of collision avoidance.

3.2.12 Constellation active debris removal

Along with the proposals for large constellations, a number of organisations have suggested that dedicated active debris removal missions could be used to clear the constellation of failed satellites. Such removal operations would benefit from the consistent constellation satellite design (which could include external features designed with removal in mind) and similar orbits, which could significantly reduce the cost and technical difficulty.

The DAMAGE model was used to investigate the role that active debris removal (ADR) could play in reducing the impact of the constellation on the LEO environment. For this study, the variable of interest was the proportion of failed satellites to remove, with five removal rates investigated (5%, 10%, 20%, 40% and 60%) in addition to the baseline (no removals) case. It was assumed that the removal of a failed satellite from the constellation orbit would be achieved by transferring the satellite to a disposal orbit with a lifetime of 25 years. Failed satellites were selected for removal based on the age of the satellite, given that the usual removal criteria (mass × collision probability) would have likely resulted in removal rankings that were effectively random. For the simulations reported here, it was also assumed that the removals were 100% successful. The results from the simulations are shown in Figure 14.

Removing 20% of the failed constellation satellites each year resulted in a 12% decrease in the number of objects by the end of the projection period, and an 18% decrease in the number of catastrophic collisions. The effectiveness of the debris removal diminished for higher removal rates so it is likely that a trade-off, in terms of the removal rate and cost, would be required to establish the optimal approach to use.

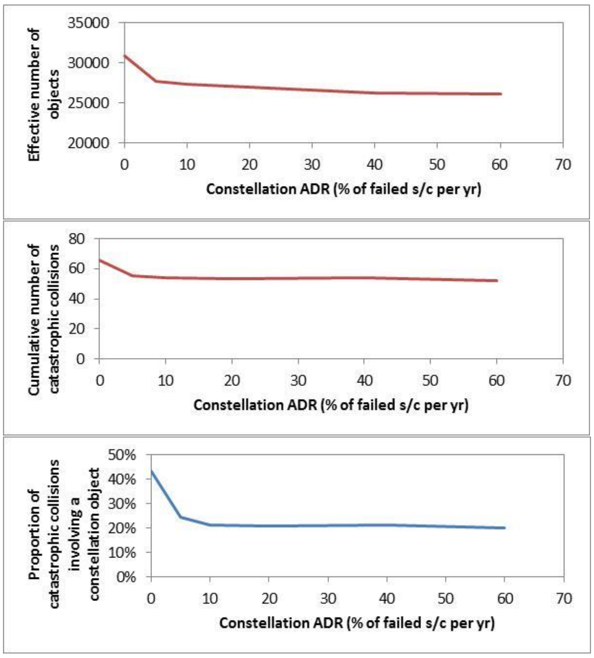


Figure 14.Effect of the removal of failed constellation satellites on the number of objects and the number of catastrophic collisions, computed by DAMAGE.

The removal of failed satellites from the constellation decreased the proportion of catastrophic collisions that involved a constellation object (bottom panel of Figure 14) and significantly reduced the proportion of self-induced collisions.

In fact, only 21% of all catastrophic collisions in LEO involved a constellation object when 20% of the failed constellation satellites were removed each year, and only 13% of these were self-induced, constellation-versus-constellation collisions. The benefits achieved through the removal of the constellation satellites remain, in spite of the addition of the failed removal satellites. Indeed, for a removal rate of 20% and a success rate of 80%, there was still a 14% decrease in the number of objects by the end of the projection period, and a 15% decrease in the number of catastrophic collisions. These findings again highlight the benefits that arise from the prevention of a build-up of a population of failed constellation satellites. In addition, the results suggest that taking action to reduce the population of failed constellation satellites is better than no action, even if there is some risk.

3.3 Small satellites

The small satellite baseline scenario was investigated using DAMAGE and LUCA. For both models, the results show a clear increase in both the number of objects on orbit and the cumulative number of catastrophic collisions over time when compared to the reference case (Figure 15 and Figure 16). Looking at the DAMAGE results only, over the whole simulation time frame, the number of objects increased on average by a factor of about 2.7. For LUCA, the number objects over time increased by a factor of about 1.6 over the complete simulation time frame

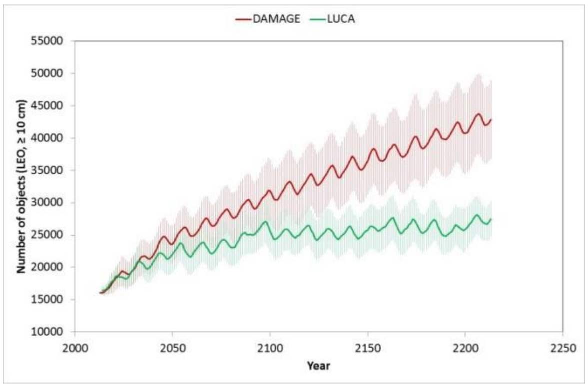


Figure 15. Effective number of objects ≥ 10 cm over the projection period for the small satellites baseline case.

The sections below describe the results obtained by varying the small satellite parameters, presented in order of their impact on the space debris environment. Only the results from cases investigated using DAMAGE and LUCA are presented. Further details and results from the other cases are reported in [8].

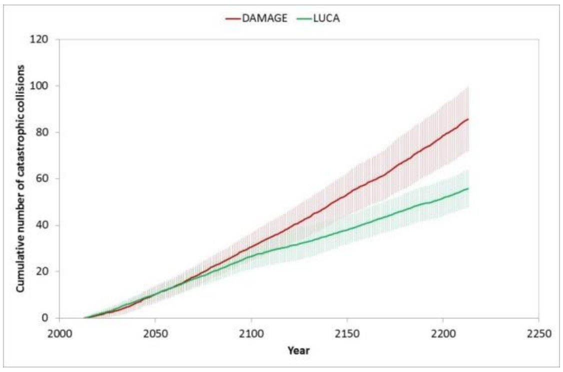


Figure 16. Cumulative number of catastrophic collisions for the small satellites baseline case.

3.3.1 Background behaviour

The behaviour of the background population was varied with respect to the PMD success rate (30%, 60%, or 90%), the disposal orbital lifetime (10 years or 25 years) as well as the launch rate (standard or double launch rate). These simulations were only performed using DAMAGE and the results are shown in Figure 17.

When the background launch rate was doubled, the values of all the metrics effectively doubled. However, increasing the post-mission disposal success rate in the background from 60% to 90% led to a decrease in the criticality norms by values between 31% and 49%, depending on the other parameters. The use of disposal orbits with shorter lifetimes provided further benefits.

Two background explosion rates were also investigated using DAMAGE: two and five explosions per year. The impact of two explosions per year was no significant (both criticality values remained below 1.0 with respect to the small satellite baseline case). However, the results from the five explosions per year case demonstrated a statistically significant impact on the long-term evolution of the number of objects. Overall, the impact was higher for the number of objects compared with the impact on the cumulative number of collisions.

3.3.2 Small satellite release altitude

The impact of the release altitudes of the small satellites was investigated using DAMAGE and LUCA. Two variations from the baseline were performed: one, in which small satellites were launched to lower altitudes, and one which they were launched into higher altitudes. For this, the underlying distributions to control the small satellite launch altitudes were varied (see [8] for more details). In addition to the release altitude, the number of dedicated launches was varied in the low and the high release altitude scenario: 80% of all small satellites were launched using dedicated launchers rather than 50%.

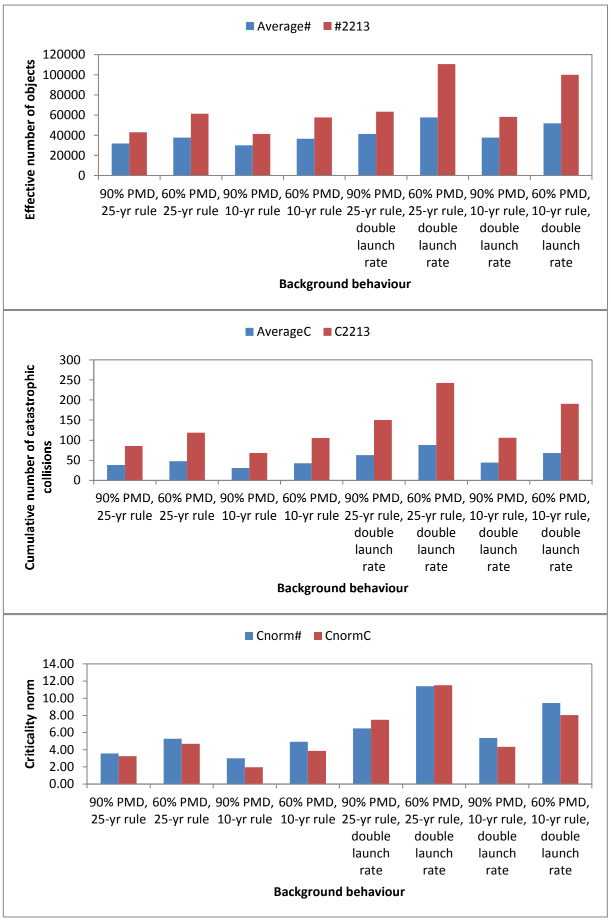


Figure 17. Effect of background launch traffic and disposal behaviour on key summary metrics computed by DAMAGE.

The results are shown in Figure 18 (both criticality norms correlate with R^2 ~ 1.0 between LUCA and DAMAGE). Increasing the number of dedicated small satellite launches had little impact on the derived metrics. On the other hand, the release of small satellites into higher orbits led to greater impacts on the environment, in terms of the number of objects and the number of catastrophic collisions. This is especially the case for the high altitude variation. The reason for the increase is simply the exponentially increasing lifetime of small satellites at the higher altitudes, the increased collision probabilities of the small satellites due to their extended lifetimes, and the extended lifetimes of fragment clouds, created during collisions involving small satellites. The results provide some evidence for measures that limit the release of small satellites at high altitudes, where their lifetimes are higher than the recommended 25 years.

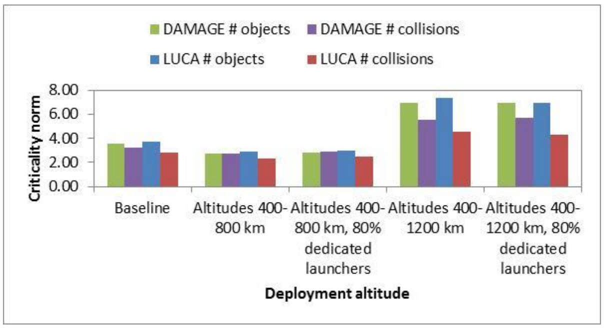


Figure 18. Effect of small satellite release altitude on criticality norm metrics computed by DAMAGE and LUCA.

3.3.3 Small satellite launch rate

To assess the impact of the small satellite launch rate, three variations were performed (Figure 1): (1) a fixed, low launch rate, similar to the rates observed today; (2) a medium increase in launch rate until a saturation at 270 small satellites per year was achieved; and (3) a high increase in launch rate to a saturation of 540 small satellites per year.

The results indicated that the small satellites launch rate directly translated into a proportional increase of all the measured metrics (some shown in Figure 19). Furthermore, the increase in both numbers of objects and collisions, as well as the criticality norms, correlate well for both models (R > 0.99).

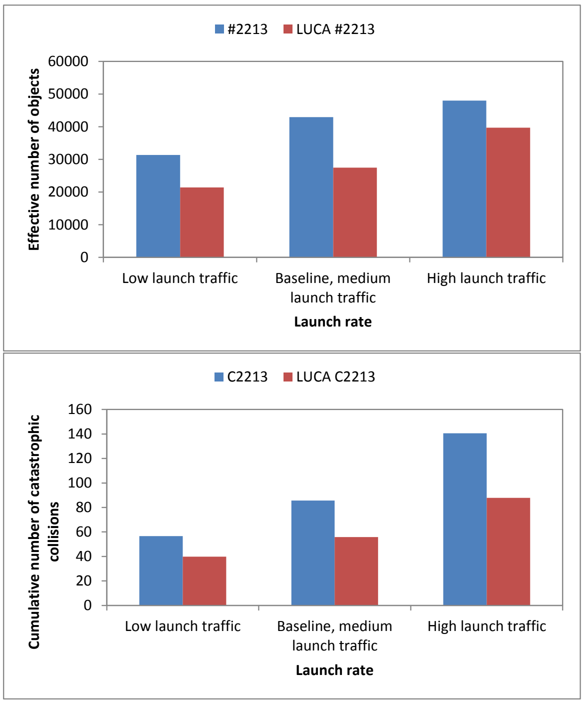


Figure 19. Effect of small satellite launch rate on number of objects and catastrophic collisions computed by DAMAGE and LUCA.

3.3.4 Other small satellite parameters

Several other parameters were investigated in the context of the study. These included the size of the small satellites, disposal of small satellites (through the application of propulsion), collision avoidance, and the deployment to swarms and constellations. The results of those investigations are reported in [8].

3.4 Constellation and small satellites

Of particular interest to the community, is the combined impact arising from the deployment of large constellations and an increasing release of small satellites into the LEO environment. To provide some insight into this future possibility, DAMAGE was used to investigate a number of scenarios featuring the baseline constellation and the baseline small satellite launch activity. The scenarios included constellation post-mission disposal based on fixed 400 × 1100 km orbits and also based on a 25-year residual lifetime.

As expected, the combined large constellation and small satellite traffic produced a higher number of objects and a higher number of catastrophic collisions, on average, than the cases featuring only one of those elements. In general, the baseline small satellite traffic had a greater impact on the environment than the large constellation, but the relative changes arising from the combined case were still significant. Including the small satellite traffic with the constellation resulted in 63.9% more objects and 90.8% more catastrophic collisions in LEO by the year 2213 than the constellation alone. The change with respect to the small satellite traffic alone was 17.6% and 46% for the number of objects and the number of catastrophic collisions, respectively.

4 DISCUSSION

4.1 Large constellations

Consistently with previous studies, the most influential aspect on the future space debris environment is the post mission disposal of spacecraft and rocket bodies. The impact of compliance below 90% for the constellation has the most substantial impact on the environment regardless of the metric used. There is substantial benefit in maximising the reliability/success of post mission disposal.

In some cases, the use of electric propulsion can be more efficient than having satellites delivered directly to the target orbit. Importantly, it increases the robustness of the system to failures and to post mission disposal failures. It is clearly evident in the data that a low deployment altitude effectively raises the compliance with post mission disposal requirements by having both rocket body PMD failures and dead-on-arrival (DOA) failures naturally compliant with PMD guidelines. At the same time, satellites that use electric propulsion will require larger solar arrays to meet the relatively high power requirements of those systems, which will increase the cross-sectional area exposed to impacts and could have a negative impact on the environment. Ultimately, there is a trade off with the collision area.

The number of satellites has a significant effect. It seems possible for constellations consisting of up to 1500 satellites to have a minimal effect on the environment. In order to achieve this, an appropriate altitude must be selected, and the satellites themselves must be relatively small. The characteristics of the satellites themselves, particularly the collision (projected) area, have a high sensitivity demonstrating that an influence on the environment should be considered at the satellite design stage. Further environmental benefits can be observed from increasing the satellite lifetimes, thereby reducing the replenishment launch requirements and by reducing the lifetime of the constellation operations.

Further, the benefit of ADR can be seen in the results, with a reasonable impact if at least 5% of failed satellites are removed. Over the constellation lifetime, this is of the order of one satellite per year, which appears feasible given the number of satellite launches. Higher impacts can be observed with higher removal rates. It is worth noting that similar benefits can be obtained by extension of the satellite lifetimes, which has the potential to be a cheaper solution, so this also provides an interesting trade-off for industry.

There is some vulnerability to the behaviour of the background population. Clearly, where operators are less compliant with space debris mitigation guidelines, the existence of a large number of operational satellites provides an increased risk, even if the constellation operators are diligent. The impact of the constellation is increased if the compliance of the background population with mitigation guidelines is poor.

These results should provide some reassurance: potential negative impacts of a large constellation can be reduced through careful design and operation. Clearly, some of the design and operation choices will involve important trade-offs (e.g. with respect to coverage, cost, and other satellite characteristics) that will require detailed analysis, but a key finding is that the impact on the environment can be addressed.

4.2 Small satellites

The most sensitive parameter in the simulations is the behaviour of the background population. Therefore, the measures which can be taken to mitigate against the impact of small satellite numbers are vulnerable to the behaviour of the general satellite population.

Of the scenarios where the background behaviour is good, it is clear that the key aspects affecting the impact of small satellites are the number of satellites, the altitudes of deployment and the size of the satellites. Where there are dedicated launches operating to deploy satellites at lower altitudes, especially where these are within the 25-year lifetime domain, a reduced impact on the environment can be observed. This consolidates the concern that unmanoeuvrable small satellites deployed at higher, more populous, altitudes can remain a source of collision risks. It is noticeable in the results reported in [8] that this effect can be mitigated against where the small satellites have a collision avoidance capability, and this capability would be recommended for small satellite missions at higher altitudes.

The trend towards increasing small satellite sizes is expected to have a significant impact on the environment according to the results (reported in [8]). Again, collision avoidance capability has some mitigating impact. Where this propulsive system is also able to provide a de-orbit capability, increased benefit is observed. This suggests that the guidelines for the de-orbit of small satellites should be similar to other satellites if deployed at sufficiently high altitude.

5 CONCLUSIONS

Most opportunities for risk reduction come from measures that limit exposure of the orbital object population to constellation and small satellite traffic. Importantly, this is not simply a case of launching to altitudes that are sparsely populated. Further, only one of these measures is represented in existing space debris mitigation guidelines: post-mission disposal.

Given the innate complexity involved in constellation design and operation, and the relatively low number of operators, it may be better to address the risks posed by large constellations on a case-by-case basis. In contrast, there are fewer opportunities overall to mitigate the impacts of small satellites. For the most part, this is due to the constraints on the design of CubeSats. Without the ability to perform post-mission disposal, there is currently no overlap with existing space debris mitigation guidelines; compliance with the so-called “25-year rule” is typically achieved through launch to low altitudes but this can’t always be achieved. In addition, the small satellite community is large and made up of a diverse set of actors, which makes it difficult to develop a case-by-case assessment approach. Consequently, there is perhaps a need to consider additional space debris mitigation guidelines for small satellites and CubeSats given the need to communicate responsibilities widely. However, there is a trade-off: imposing restrictions on small satellite missions could forfeit many of the advantages offered by them. In particular, the cost impact could be severe and affect the commercial viability of missions.

Nevertheless, the simulation results suggest that it is important to have regulation of the small satellite population in order to mitigate the effects on the environment. The existing space debris mitigation guidelines already provide the basis; but evidence of the past decade has shown that satellites have a patchy record of compliance, at best [14]. Enforcement, perhaps, will provide a more robust way to mitigate the impacts of small satellites on the environment.

6 ACKNOWLEDGEMENTS

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